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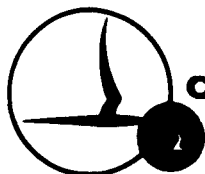
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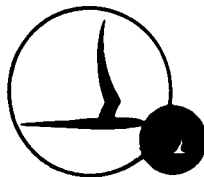
SHORT PULSE LASERS

Final Report
Internal Research Program 86-888
CAL Report No. UB-1613-E-1
October 1962



CORNELL AERONAUTICAL LABORATORY, INC.

OF CORNELL UNIVERSITY, BUFFALO 81, N. Y.



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BUFFALO 21, NEW YORK

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Prepared by:

R. F. Schneeberger

R. F. Schneeberger
Principal Engineer
Electronics Department

Approved by:

W. T. Harpster

W. T. Harpster, Head
Radar Techniques Section

C. W. Miller

C. W. Miller, Head
Electronics Department

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1. PURPOSE

The object of this program, as noted in the program proposals, Refs. 1 and 2, was to determine the feasibility of obtaining Laser operation by exciting Ruby crystals with short-duration, high-intensity pulses of light obtained from an arc source. In addition, a secondary goal, the fabrication, operation, and instrumentation of a standard-type, long-pulse Laser was to be undertaken. The latter object was included to allow a broader investigation into the physics of Laser problems and to serve as a basis for comparison of short-pulse results. Underlying these experimental purposes is the basic interest, namely, that the Laser is characterized by the unique features of spatial and temporal coherence of the output, giving a light source having a single wavelength output and, hence, properties similar to radio frequency generators but at a much higher frequency.

2. SUMMARY

The two programs noted above were carried out to the limit of the program funds available and, in both cases, the intended scope of work could not be completed. However, the work performed was sufficient to allow specific conclusions to be drawn. A long-pulse Laser was fabricated and was successfully operated over a period of four months. A discussion of the design, operation, tests and technical difficulties encountered is contained in Section 6. Several experimental attempts were made to pump Ruby with short-duration pulses, in which it was found that Laser operation could not be obtained. The experiments, data and analysis of results are discussed in Section 7. Finally, since this report will in many cases serve as an introduction to the Laser field, a brief discussion of Laser theory is presented in Section 5.

3. CONCLUSIONS

It was found that the main objective of this program, the determination of the feasibility of using short pulses for Laser pumping sources, could not be demonstrated. The reason for this result has been established, namely, that for the size of crystals chosen, sufficient pump power was not

available to obtain population inversion required for Laser operation. However, it cannot be concluded that the method would fail in all cases. If the size of the crystal was reduced sufficiently, or if a four-level Laser material (as opposed to the three-level type, Ruby - $\text{Cr}_2\text{Al}_2\text{O}_3$) were employed, calculations show that population inversion and, consequently, Laser operation, should result.

The construction and operation of the long-pulse Laser followed the work of other groups and, as such, led to no new scientific information. However, the problems associated with the design and operation of the long-pulse Laser, as noted in Section 6, indicate the acquisition of some fundamental background in Laser mechanics. The actual Laser result consisted of a unit capable of radiating .4 kilowatt of peak power at 6943\AA for a period of approximately $500\ \mu\text{s}$. It was not possible to measure the degree of coherence or output angular characteristics because of equipment failure and time and cost limitations. However, the observed output compared quite favorably to that obtained by other groups.

4. INTRODUCTION

The application of the Laser to the Pulsed Light Ranging problem was apparent from the time of the first disclosures in July 1960, by Dr. T. H. Maiman of Hughes Research Laboratories. It was, in fact, a device of the type sought eagerly by the Pulsed Light Field for a number of years. The early models of Lasers had, unfortunately, a distinct limitation in application in the range finder task because the output consisted of a long series of short-random pulses of light. While such pulses could be employed, the application was complex, requiring complete physical separation of the transmitter and receiver to avoid backscatter problems and a correlation or spectrum analyzer-type receiver to operate on the pulse sequence.

Realizing the necessity for single-pulse Laser output, it was proposed that the subject program be instituted to determine the feasibility of short-pulse pumping. It is to be noted also that through previous effort an arc source capable of supplying very high intensity light for

short-time durations was available. It is also to be noted that at the time of the proposal (and today), much speculation was being made as to the nature and extent of all the physical processes involved in Laser operation. As such, the program goal could be more basically described as the study of the rate limits of the population inversion process and rate of decay or time constants of atomic-excited states, specifically those of Ruby.

The subject program was initiated prior to any announced success in short-pulse work. However, during the course of the program, several organizations have made disclosures in this area. The methods employed were radically different from that employed here and are worth noting here because of the large amount of power output obtained and the possibility of application to many instrumentation programs. Of the several methods, that of "Q Spoiling" and "Hair Triggering" appear to be the most successful. Both methods employ long-pulse pumping as in the standard-type Laser, but oscillations are purposely prevented. When the Laser material is saturated with excited ions, a transient is introduced which causes a sudden coherent decay of atoms to their ground state. In this method, a very large percentage of the ions can be made to emit during the transient period and, hence, the peak power is limited primarily by the size and quality of the Laser material. In the short pulse method employed here, the number of ions that can be excited is severely limited by the available pump power, hence, the size of the crystal is a significant factor in the Laser design employing this approach.

5. THEORY

The Laser (Light Amplification through Stimulated Emission of Resonance Radiation) is a device which depends upon the radiation of an atomic system which is not in thermal equilibrium for any positive temperature $T^{\circ}\text{K}$. The physical processes involve the interaction between the atomic system, electromagnetic waves, and resonant structures. It is the intent in this Section to present a description of the processes involved. The detailed analysis is beyond the scope of this introduction but can be pursued by review of the reference material. The subject is introduced here by considering the absorption coefficient of the atomic system.

It is well known that atoms can exist only in certain allowed energy states and that in interaction with electromagnetic waves, only specific wavelengths can be absorbed or emitted - those wavelengths which correspond to the differences between energy levels in the atom. It is also well known that the lower energy states are the most heavily populated, the populations obeying the Boltzmann law, $N_i = N_0 e^{-\frac{E_i - E_0}{kT}}$, when the atomic system is in thermal equilibrium at some temperature $T^\circ k$. Now, in interaction with electromagnetic energy of the characteristic wavelength, atoms in the ground state can absorb a photon and exist in the excited state or an atom in the excited state (considering only two possible states) can emit a photon and subsequently exist in the ground state. A probability is associated with each of these transitions, the probability being dependent upon absorption or emission cross section, and upon the number of atoms in each state. Because of the Boltzmann distribution, it can be concluded that the probability for absorption is much greater than the probability for emission even for small energy level separation. If, then, e - m energy of the characteristic wavelength is passed through this two-state system in thermodynamic equilibrium, it will be observed that the transmitted beam is of reduced intensity, that energy has been absorbed by the system. Both of the processes, absorption and emission, are considered here as stimulated processes, that is, the processes take place in time phase and direction with the e - m wave.

In addition to the above processes, that of spontaneous emission also takes place. Suppose that in the above system the incident wave had been present for a time sufficient to attain equilibrium at some high temperature $T' k$. If, then, the excitation were removed, the atomic system would not remain at temperature T' because the system is no longer in equilibrium with its surroundings. It would again decay to the temperature T_0 . The system loses energy through the spontaneous emission of e - m energy with excited atoms again moving to the ground state. Spontaneous emission is a random process both in time and direction. It is not to be concluded that spontaneous emission takes place only with the removal of the incident beam. It is a process which takes place continually in nature, in the low-lying atomic energy levels at room temperature, for example.

It is therefore also occurring when the incident beam is present above and is indicated physically by scattering of light out of the direction of the beam. An atom, when excited to a higher energy, will in nearly all cases remain in that level for approximately 10^{-8} seconds before emitting spontaneously and returning to the ground state. There exists certain more-or-less-forbidden transitions in atomic spectra, however, in which atoms will remain in the excited state for seconds, and even years, before a spontaneous emission takes place.

It has been shown that absorption takes place in appropriately excited atomic systems in thermal equilibrium. The Laser process requires emission to be the predominant process. This can be accomplished in the example above if the number of atoms in the excited state exceeds the number in the ground state, for then the probability of induced emission will exceed the probability for absorption. The problem then becomes one of finding an atomic system in which more than half of the atoms can be placed in the excited state in a time short compared to the spontaneous emission rate. This condition is known as population inversion or state of "Negative Temperature." The latter designation is due to the fact that only a negative temperature will satisfy the Boltzmann equation. It was noted above that lifetimes in the excited states in most cases are only of the order of 10^{-8} seconds. Because of the time responses of pump sources (incident beams) and the limited time to obtain stimulated or induced emission, these systems up to this time have offered little possibility for Laser operation. However, for those systems which contain forbidden transitions, that is, long lifetimes in excited states, sufficient time is available for the attainment of inverted populations with realistic pump powers. Systems possessing long lifetimes in excited states are generally said to fluoresce. These systems cannot, however, be described by the two-level energy diagram depicted above.

In considering useful atomic systems, that of Ruby is first discussed. Typically, this material is a grown single crystal of Aluminum Oxide (Al_2O_3) containing small percentages (typically .03 to .08%) of chromium doping. The chromium ion situated in the crystal is the element on which the pumping process is actually carried out. The ions are in the

ground state under equilibrium conditions. When, however, light in the green region of the spectrum is made incident on the material, the atoms are excited to the upper state as shown in Figure 1 below. Atoms will remain in this state only for 10^{-8} secs., after which they decay to the metastable state (fluorescent level) because of spontaneous radiation or other processes. (In Ruby, the decay is due to a radiationless process.) The mean life in the metastable state for Ruby is of the order of 10^{-3} seconds. Hence, if at least half the atoms in the ground state (chromium ions only) can be pumped to the upper state and decay to the metastable level in 10^{-3} seconds, the conditions for population inversion have been reached and the introduction of an electromagnetic field of the wavelength corresponding to the metastable-to-ground-state transition is introduced, amplification rather than absorption will take place.

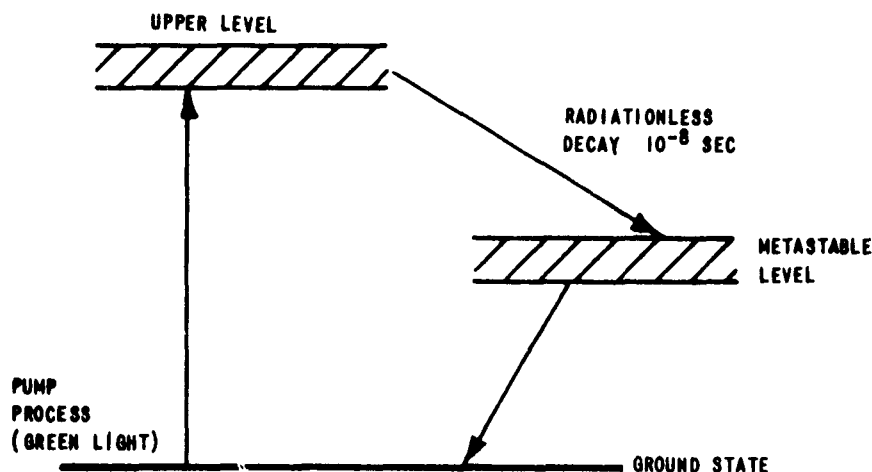


Figure 1 THREE-LEVEL LASER DIAGRAM

Ruby was the material employed in the first successful Laser and has continued to be one of the most popular of the useful materials. However, from an energy utilization or efficiency standpoint, it is less desirable than some others. It is described as a GTS system (Ground Terminal State), as noted in Figure 1 above. Consider now, however, a system in which the stimulated emission takes place between the metastable level and a terminal state lying above the ground state, as shown in Figure 2.

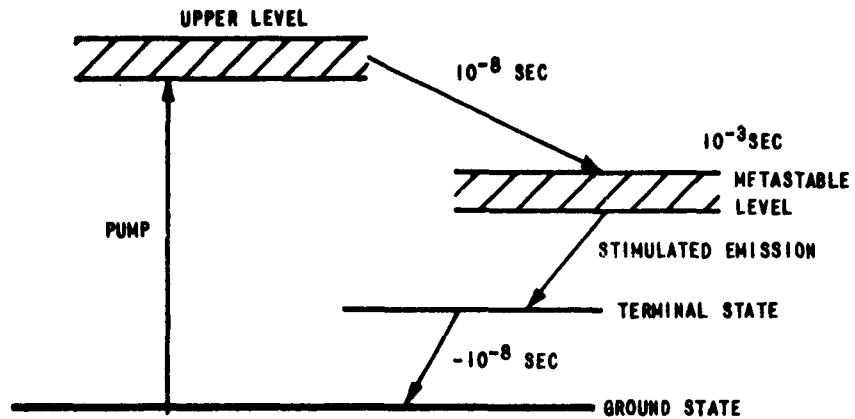


Figure 2 FOUR-LEVEL LASER DIAGRAM

Now, if with no pump excitation the terminal state lies a fraction of an electron volt above the ground state, it will be almost completely unpopulated even at room temperature. Then the number of atoms which must be excited to the metastable level through the upper level to obtain population inversion with respect to the terminal state is much reduced from that required of Ruby ($1/2 N$), so that significantly less power is required to obtain inversion. This system, a four-level system, is characteristic of Neodymium, which has also proved to be a successful Laser material when used as a doping material in glass.

Consider now, a sample of active material with an excess of atoms in the excited state, the sample being in the form of a sphere. If, at any atomic site in the sphere, an atom should emit a photon due to spontaneous emission, the resulting e - m wave will interact with other excited atoms, inducing them to radiate likewise, and a growing wave in the direction of the spontaneously emitted photon will result. Since the spontaneous emission process is random over any period of time longer than 10^{-3} secs., a number of such growing waves would be observed travelling in completely random directions. These waves would continue to grow until they passed through the surface. Since a large number of waves would be generated in direct proportion to the number of spontaneous emissions which occur, the power in each wave would be small and the total power would be evenly distributed throughout the surface of the sphere.

If, instead of a sphere, a long cylindrical sample were chosen, again, due to the randomness of spontaneous emission, waves would be

generated travelling in many directions with respect to, say, the longitudinal axis of the sample. However, those travelling toward the cylindrical surfaces would encounter relatively few excited atoms before passing through the surface and would show little growth, while those travelling along the cylindrical axis would encounter many excited atoms and would develop into waves of very high intensity. In fact, this technique - the selection of highest gain, lowest loss modes, is employed in Laser design. The selection of modes or a single mode of propagation can be enhanced by the use of resonant structures. The most generally used resonant system consists of a cylindrical sample with nearly total internal-reflection end surfaces, a Fabry Perot-type interferometer. In this system, only the modes propagated along the cylinder axis are strongly enhanced by stimulated emission, all other modes being lossy and therefore entering the design problems only in determining the system losses and the excess of atoms required in the excited state. In operation, then, in a system of excited atomic states a spontaneous emission occurs which, through the e - m field generated, interacts with other excited atoms and through stimulated emission causes a growing wave to be generated. If this wave travels in the direction of the low-loss mode of the structure, a wave continually growing, making many passes through the material because of reflections (that is, the selected mode) will be generated. In general, one reflector is made slightly transparent in order to obtain power from the system. Waves generated in the lossy modes rapidly pass through a surface and enter into the process no further.

The system description above relates to oscillators. Amplifiers can also be formed, again by using a cylindrical structure but with the reflecting surfaces removed. If, then, an inverted population exists, and an electromagnetic wave of the characteristic wavelength is introduced along the cylindrical axis, this wave will grow in traversing the medium. Note, however, that the amplification is not noiseless because spontaneous emissions along the axis are also statistically possible.

This descriptive presentation of Laser theory has been quite general but is applicable to most known Laser systems demonstrated to

date. The same discussion is pertinent to gas Lasers which are typically CW devices, even to the resonant structure design. In the gas Laser, however, other processes must also be taken into account, such as the influence of the buffer gas, doppler problems due to particle velocities, influences of the container walls, and the like. It must be noted, of course, that much remains to be discussed in regard to the solid Laser as well as including influence of structural defects, the mechanism of radiationless decay, and others, which subjects are beyond the scope of this introduction.

6. HIGH POWER LASER EXPERIMENT

In order to provide some Laser background and some data for low-power, short-pulse comparison purposes, a high-power Laser was designed and constructed. This unit was completed in January 1962 and tested and demonstrated for brief intervals over the next four months. A description of the design, test results and problems is given below.

a. Design

The high-power Laser is composed of five essential components: the active element (Laser crystal), the flash lamps (pump), a reflector, the power supply, and the capacitor bank. The design of the "Laser Head" is shown in Figure 3. The flash lamps are arranged such that the cylindrical reflector focuses a large percentage of the pump radiation on the Ruby crystal. The active areas of the lamps and the complete crystal are contained in the water-tight cylindrical container. The water-tight feature was included to allow continuous cooling through the use of either circulating water or liquid nitrogen. To improve the reflectivity of the cylinder, a silver coating was evaporated on the inside surfaces.

A block diagram of the power system is shown in Figure 4. The power supply and capacitor bank combination can supply a maximum energy of 1200 joules. This energy is applied directly to four GE-type FT-91 flash tubes in a series arrangement. The lamps are energized by applying a 15 Kv pulse to the flash tubes. Following the initial breakdown, the capacitor bank discharges through the lamps.

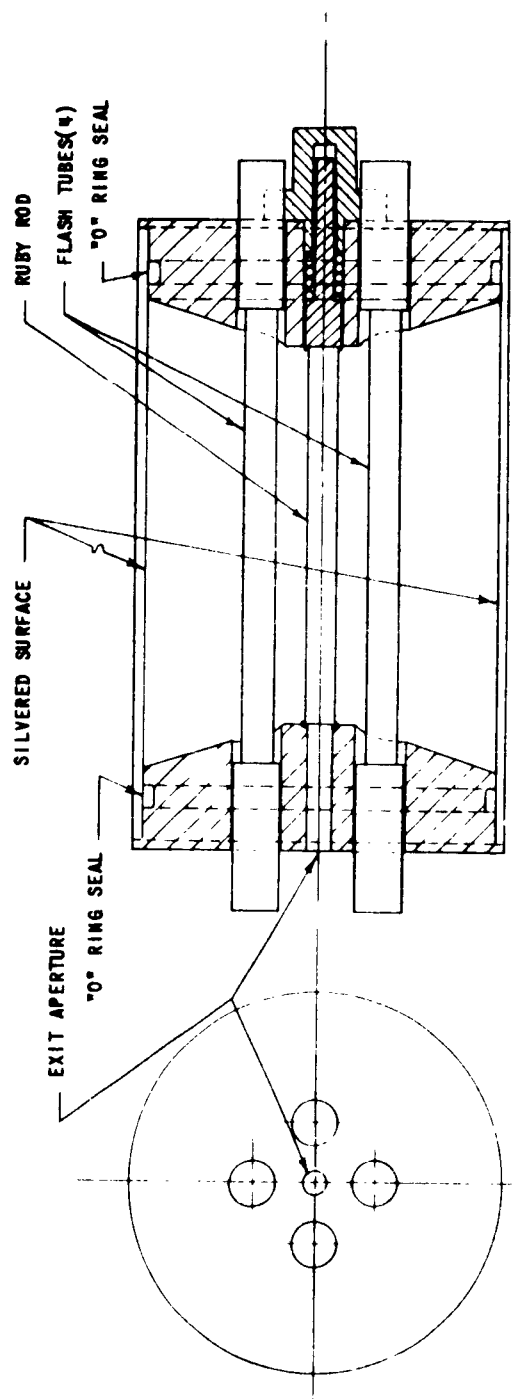


Figure 3 HIGH-POWER "LASER HEAD" DESIGN

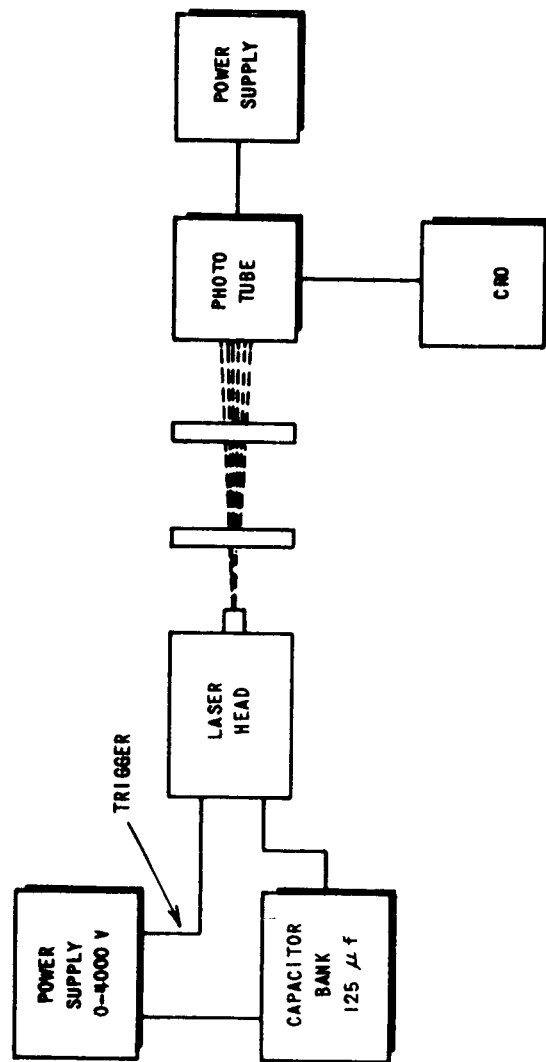


Figure 4 HIGH-POWER LASER BLOCK DIAGRAM

The active element, a Ruby crystal, was purchased as a completed item, that is, with all surfaces ground and polished to the required tolerances, and with dielectric reflecting surfaces deposited. The crystal was supplied by the Adolph Miller Company. The basic Aluminum Oxide (Al_2O_3) crystal material was doped with .04% by weight of Chromium. The transmitting surface was finished to allow 5% transmittance, 95% internal reflection.

b. Test

Following initial success of this Laser and an extended period of demonstration, a test program was initiated to determine the characteristics of the Laser output. The properties of interest were: a) Peak Power Output, b) Time Response, c) Spectral Purity, d) Beam Width, e) Energy Distribution in the Beam (or on the exit aperture). These five properties would allow the determination of efficiency, crystal quality, and degree of coherence attained. The test outline is presented in Ref. 4. It was not possible to complete the entire program because of cost limits and equipment failures. However, the data assembled was most useful in determining power level and efficiency and also allowed some direct comparison with the results published by other experimenters. In this respect, the wave forms obtained in the output are in very good agreement with other sources, particularly those of Ref. 3.

For the power output and time response measurements, a detector system composed of an RCA-type 7326 photomultiplier, a Wratten #70 gelatin filter and suitable attenuators were assembled and calibrated. The calibration procedure consisted of using a tungsten calibrated lamp and a Carl Zeiss Monochromater, then measuring the absolute amount of incident radiation at 6943\AA , which produced a given output on the detector system. The spectral response of the complete detector system is shown in Fig. 5. The system was found to transmit .0006% of the incident light, hence, for any observed deflection observed for the Laser output, the intensity of the coherent source could be established.

The results of the experiments performed are as follows. The Laser had a peak output power of .4 Kw and a total energy output of .2 joules

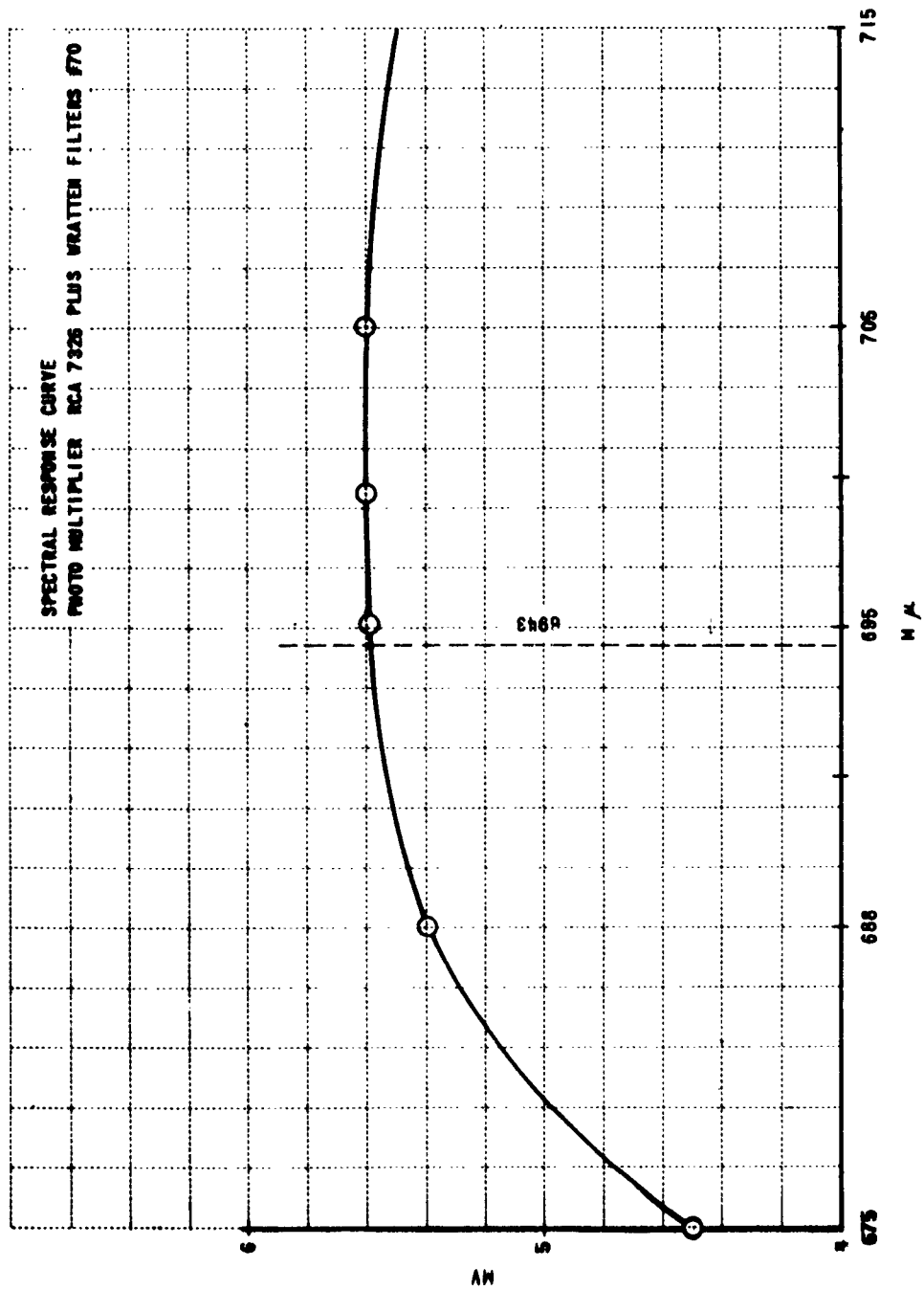


Figure 5 DETECTOR SYSTEM SPECTRAL RESPONSE

for an input of 900 joules. The efficiency of the system was approximately .02%. This figure is the same as that achieved in the initial Laser experiments in Ruby as noted in Ref. 3. However, the subject Laser could be operated at a minimum input power of 420 joules, while that of Ref. 3 had a threshold for Laser operation of 800 joules. These values, in general, are indicative of pumping efficiency and crystal quality.

A photograph of the far-field pattern of the Laser beam is shown in Figure 6. The actual spot size is about 1/4 inch in diameter and was obtained by allowing the beam to illuminate a photographic plate. In a much enlarged version of the photographic image, Figure 6, evidence of circular light and dark zones can be observed. This result is indicative of the coherence of the light and the diffraction effect of an aperture on coherent energy. In addition, the temporal response of the source is shown in the oscillograph photographs of Figure 7. The output pulse length varied from 400 to 700 microseconds, depending upon the amount of energy applied to the pump flash lamps.

c. Problems

A significant number of experimental problems arose in this phase of the program which served to both delay the completion and deplete the project finances. The most serious problem was one in which the mirrored ends of the crystal would be ruined (mirrored finish removed). This problem occurred four times during the course of the program and with each occurrence the crystal had to be reworked and replated. The apparent causes of this problem lay in the (now known) faulty materials' selection. In making the Laser housing water-tight, Teflon, rubber and epoxy seals were employed. The latter two were destroyed by the high-energy, ultra-violet light and the large amounts of heat generated in the cavity. The Teflon apparently broke down under UV and some product of this breakdown led to the disintegration of the reflecting surfaces. Another cause for this destruction was the high shock forces existing on the initiation discharge.

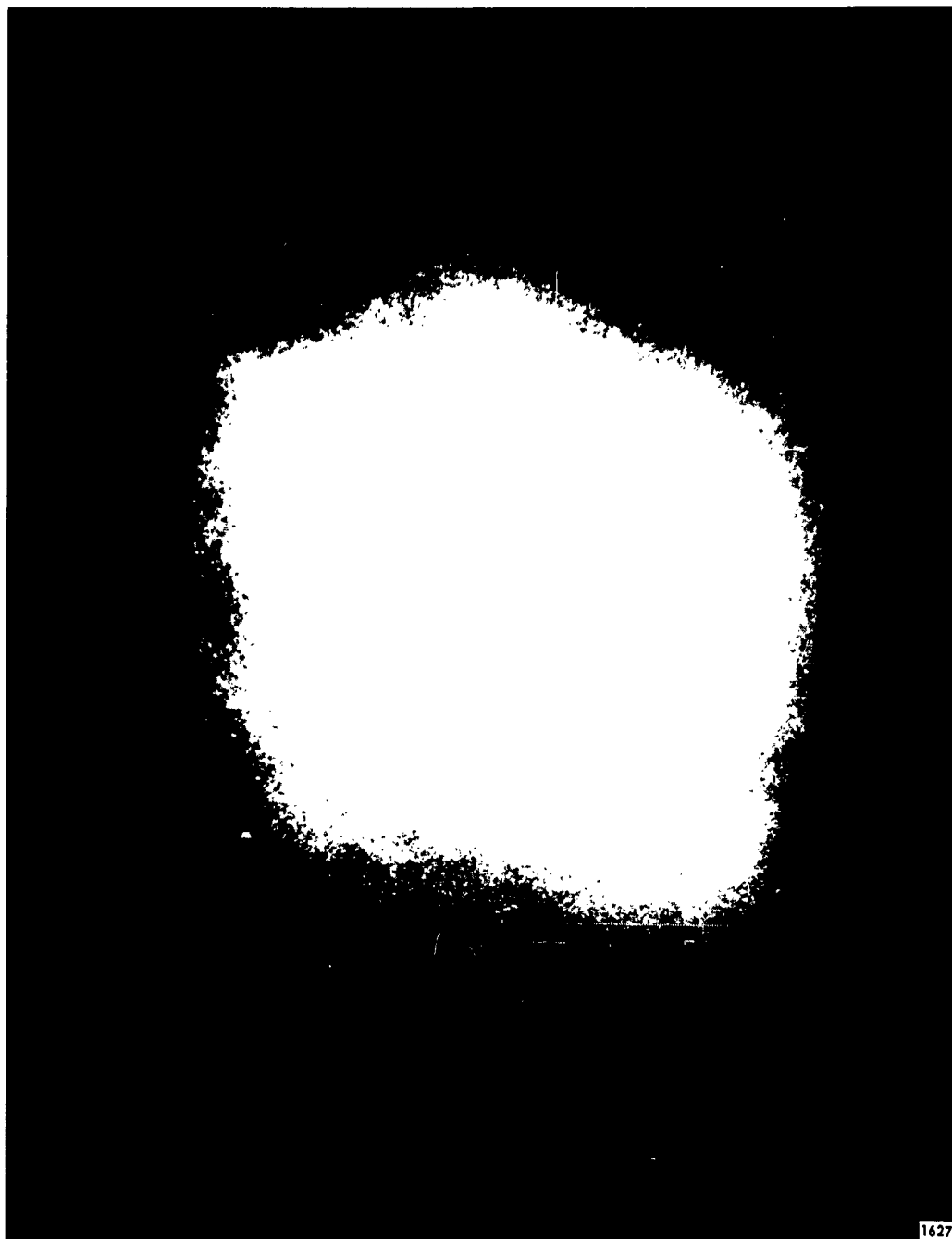
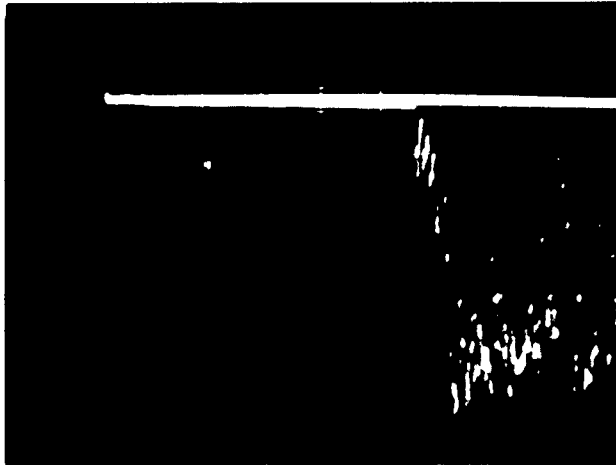
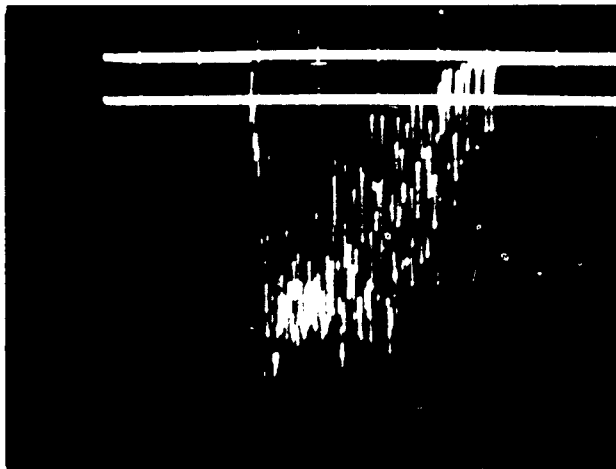


Figure 6 HIGH-POWER LASER FOR FIELD PATTERN



(a)

C(μ f)	100
V(kv)	3.5
FILTERS	1-5
SWEEP	50 μ SEC/cm
CALIBRATION	1 V/cm



(b)

C(μ f)	100
V(kv)	3.8
FILTERS	1-5
SWEEP	100 μ SEC/cm
CALIBRATION	1 V/cm

Figure 7 HIGH-POWER LASER OUTPUT TIME RESPONSE

In the last problem to be encountered, it was found that one of the flash tubes had broken down. When this unit was flashed, it exploded and caused two other tubes to be broken. The only indication of this problem was an apparent difficulty in triggering the system. It is to be noted, however, that the tubes were flashed approximately 5000 times before the catastrophic failure occurred.

7. SHORT PULSE LASER EXPERIMENTS

The basic objective of the subject Internal Research Program was the investigation of the possibility of obtaining a single short-duration output pulse from a Laser device. The usefulness of such an output was noted in the Introduction, and is further illustrated by reference to Figure 7 of the previous section. While the experimental results were negative, no basic limitations have been ~~discovered~~ and experiments might now be performed which would give positive results. The reasons for this conclusion are presented below.

It was noted in Section 4 that the first objective in Laser design is to produce a population inversion. This requires that there must be sufficient energy of the appropriate wavelengths available in the pumping source to invert the population while overcoming the coupling (pump-to-crystal) losses, and the crystal pumping efficiency (number of excited atoms per number of incident photons). Following these considerations, the quality factor of the cavity and crystal loss factors must be considered before the pumped crystal will lase. In this section, highly efficient coupling systems are seen to be easily obtained because of the small source size of the pump. Hence, the major investigation concerns the volume of material that can be pumped.

In conducting this part of the program, two experimental designs were carried out. In the first of these, a cylindrical Ruby crystal, .5 inch diameter and .5 inch long, was finished according to typical Laser specifications but with a 1/8-inch hole machined along a diameter of the cylinder mid-way between the end faces. The crystal is shown as b in Figure 8. The crystal was then placed in the spark lamp such that the electrodes of the lamp and the spark gap were positioned in the 1/8-inch hole inside the crystal. Then, on applying power to the spark lamp, at the critical gap voltage a spark discharge took place, the resulting light energy thus passing directly into the crystal material. The crystal and lamp are shown assembled in Figures 9 and 9A.

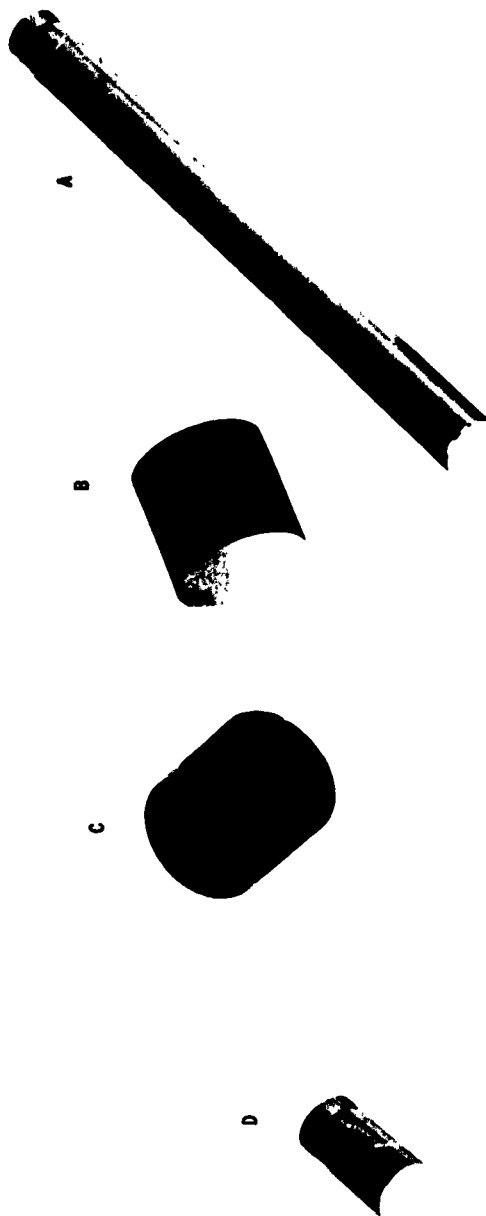


Figure 8 CRYSTALS USED IN LASER PROGRAM

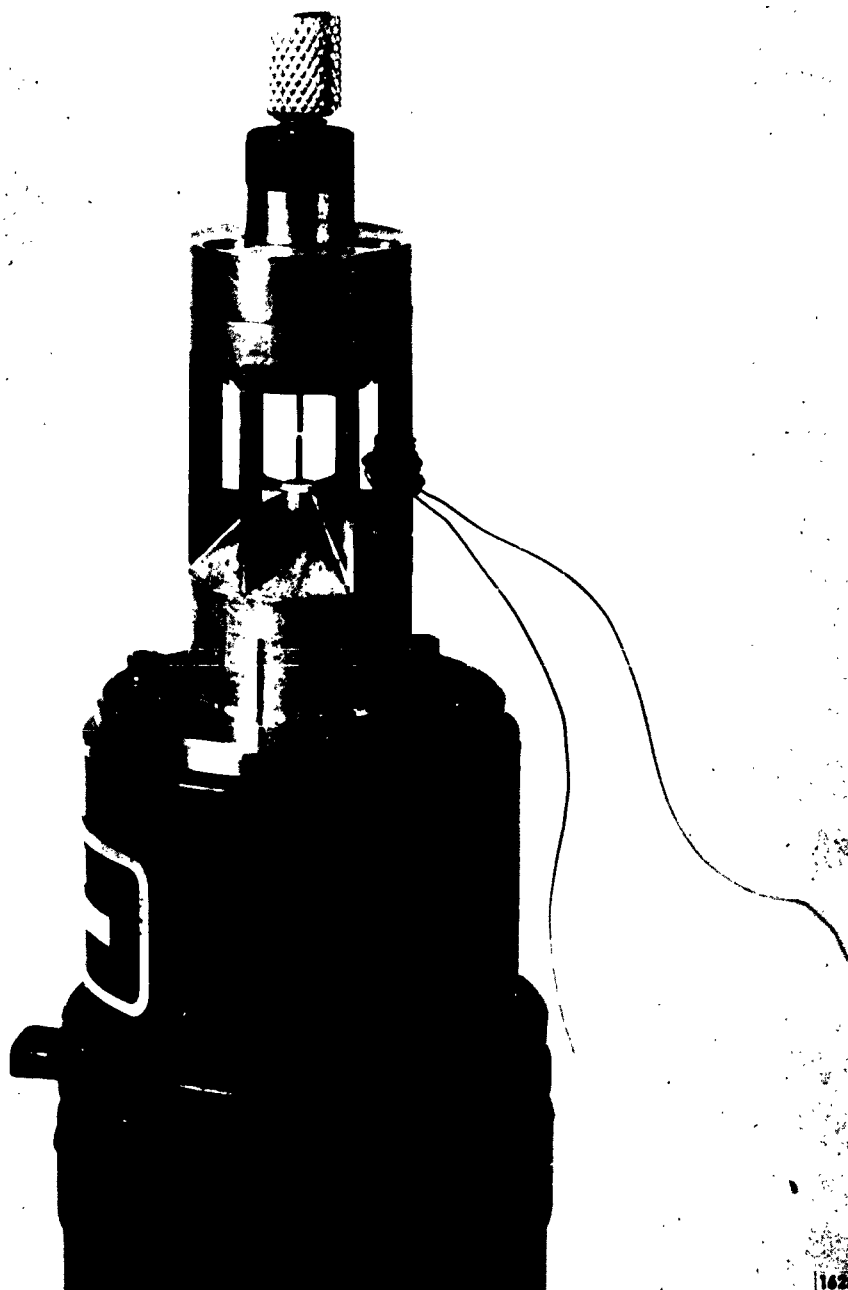


Figure 9 SPARK LAMP

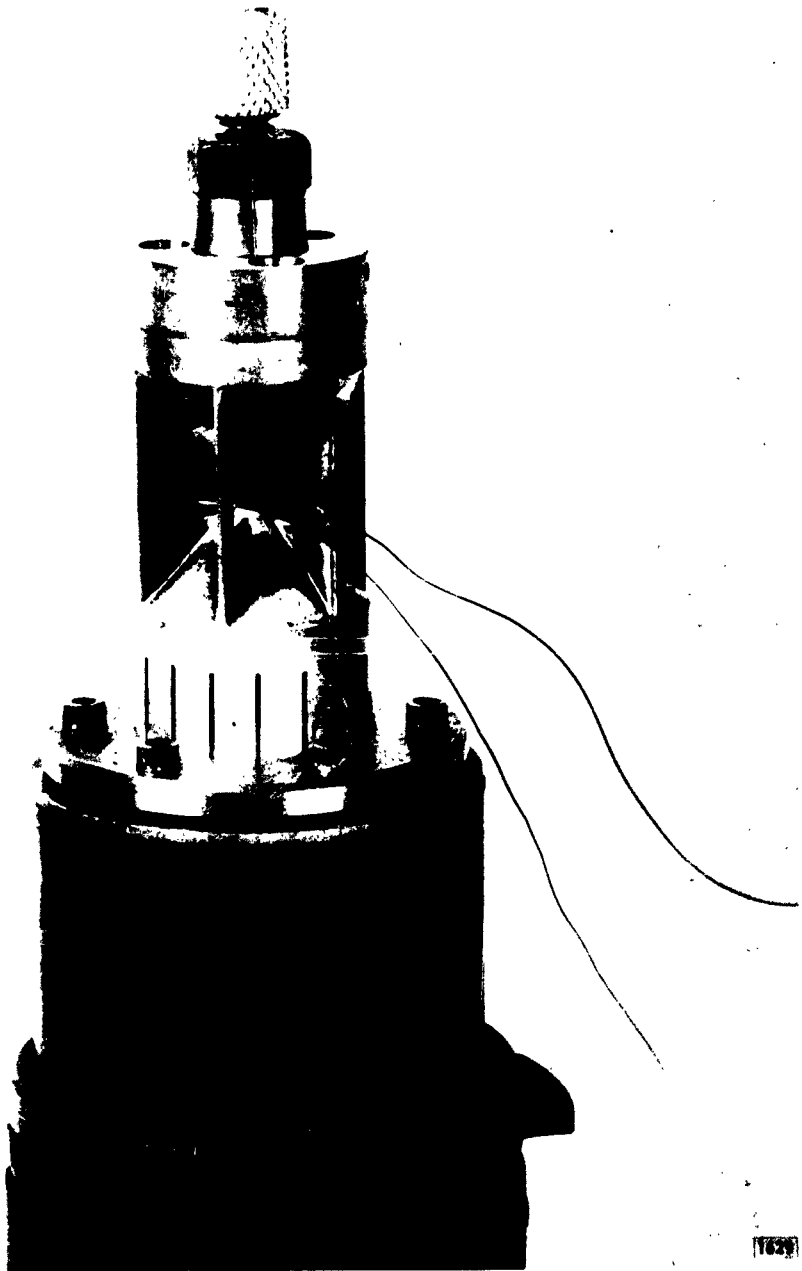


Figure 9A SPARK LAMP WITH CRYSTAL MOUNTED

Several problems were encountered in this experiment. The first, and most serious, was the undetermined effect of the hole on the properties of the Fabry Perot etalon. Secondly, all the spark and arc energy was passed through the crystal and, hence, for any appreciable repetition rate (5 cps), the crystal became overheated and the end face reflectors deteriorated rapidly. Third, in the spark discharge, material is sputtered off the electrode, as is evidenced by the increased gap length after a few pulses. The sputtered material strikes the crystal surface and becomes imbedded in that surface, rapidly making it opaque to spark light.

To eliminate these problems, the second experimental arrangement was made. This consisted of placing the spark lamp at the focus of an 18-in. paraboloidal mirror and the crystal at the focus of a second identical mirror. The mirrors were then aligned and the crystal and lamp adjusted so that the spark light focused directly on the crystal cylindrical surfaces. For this experiment no hole was required in the crystal. The system arrangement is shown in Figure 10.

The experimental results are shown in Figures 11, 12, and 13. Considering the second experiment, the lamp pulse was observed, employing an S20 photomultiplier detector, directly, as seen through a piece of lucite positioned in the mirror in place of the Laser crystal, and as seen through the Laser crystal. In all cases, the short time ($1\mu s$) response was found to be the same except in amplitude. Figure 12, a and b, show the direct and lucite scattered pulse, while Figure 11, a, shows the Ruby output pulse. On using a much longer time base and approximately a 30 x increase in gain, distinct differences could be found when observing the Ruby output. This is shown in Figure 11. Figure 11, a, shows the output of the lamp, a large negative pulse at the start of the trace, falling directly back to the base line. Figure 11, b, shows the same result when the output is taken through the lucite blank installed in the second mirror. The results in c and d, however, for the same scales as above, show a sudden drop in pulse amplitude as before, but not to the base line. Following the fast pulse, there is a long decay in output until the base line is again approached, approximately 8 milliseconds after the .4 microsecond input pulse. This result is due to the decaying fluorescence of the Laser material.

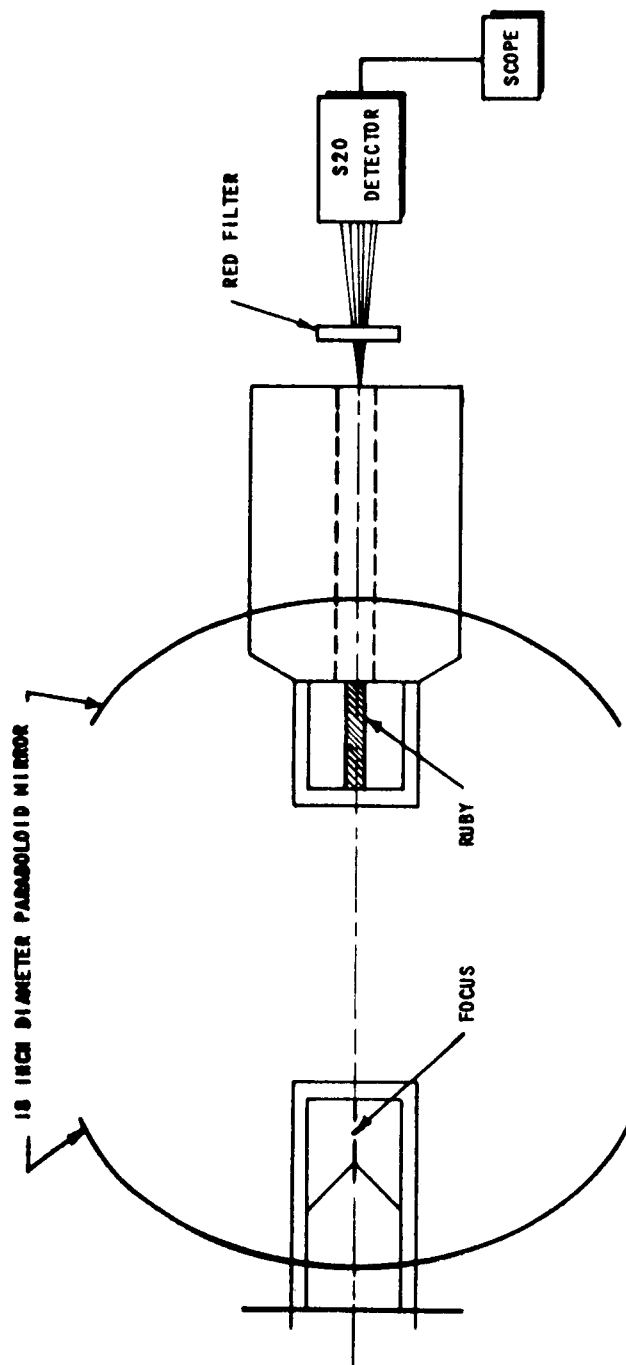
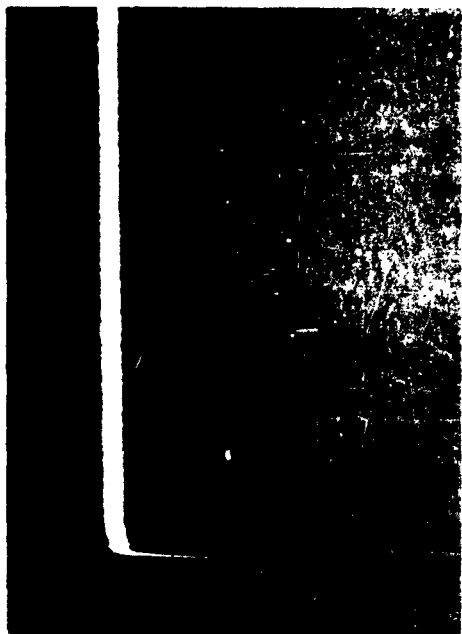
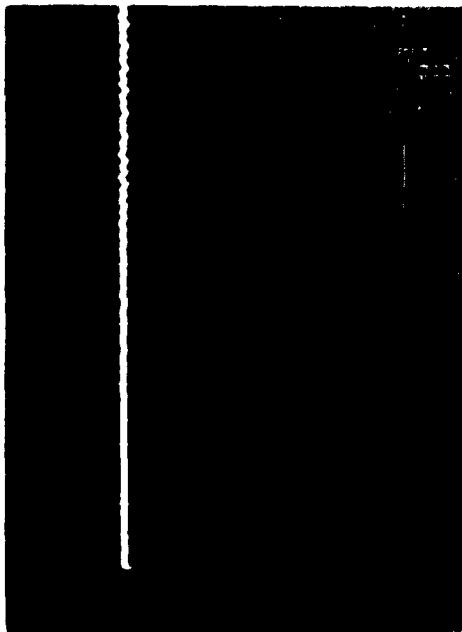


Figure 10 PARABOLOID MIRROR SYSTEM

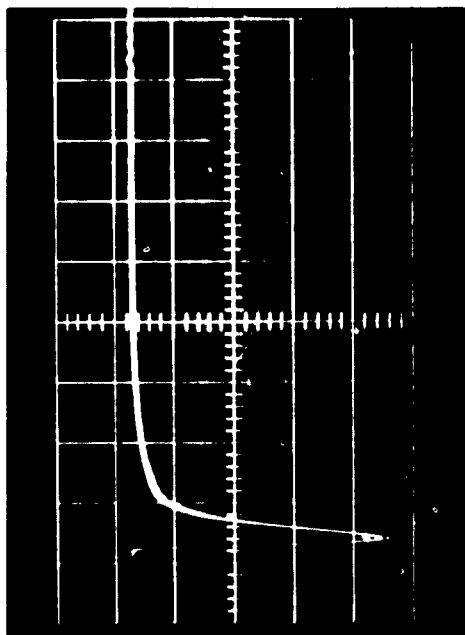


(c)

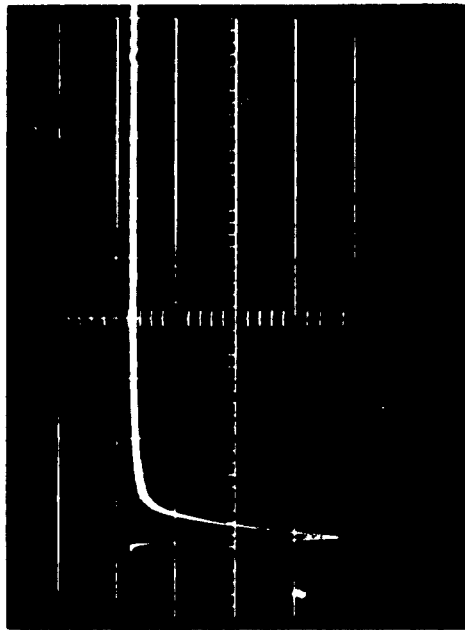


(d)

Figure 11 EXPERIMENTAL RESULTS - PARABOLOID METHOD I



(a)



(b)

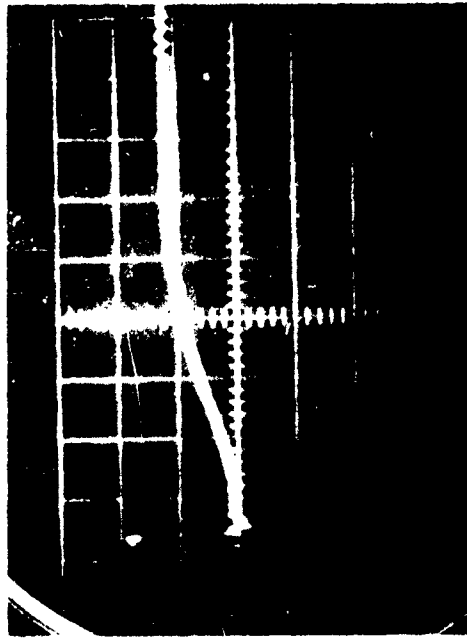
Figure 12 EXPERIMENTAL RESULTS - PARABOLOID METHOD 11



(a)



(b)



(c)



(d)

Figure 13 EXPERIMENTAL RESULTS - CONTAINED SPARK METHOD

It was concluded in the preliminary study that Laser effects should be observed approximately 3-4 milliseconds after the spark lamp pulse, since that time is the lifetime of atoms in the excited metastable state of the Ruby material. The results observed in Figure 11, c and d, show that such a conclusion was in error. Actually, the definition of "Lifetime in an Excited State" can be expressed as $N = e^{-\frac{t}{\tau}}$, where τ is specified as that value of τ at which the number of atoms in the excited state has decayed to $\frac{1}{e}$ the original population. Hence, the Ruby will fluoresce immediately on application of the spark pulse and will decay at the exponential rate noted above where $\tau \approx 3$ milliseconds. Therefore, Laser-type output should occur during or immediately following the pump pulse. This is the point at which the experimental procedure proved to be unsatisfactory. It has not been possible, using only a photomultiplier as detector, to analyze the initial pulse as seen in the Ruby output. It was necessary to perform a spectroscopic analysis on that output to determine if any fluorescence line-narrowing was taking place. The Zeiss Monochrometer was set up to pass the output light and the spectrum was observed. It was found that no line-narrowing took place and, hence, Laser operation was also not taking place.

These experimental results can be compared also to those obtained in the first experiment. Those results are shown in Figure 13, photos b, c, and d. Photo b shows the results observed on a $10 \mu\text{s}/\text{cm}$ base, and c and d show expanded views of that pulse ($1 \mu\text{s}/\text{cm}$ base). Here, it is noted that there is no initial pulse of large magnitude with respect to the fluorescent decay. Actually, the output pulse is seen to consist of two time constants, the long one (3 milliseconds) noted previously, and a much shorter one, measured from the photographs to be approximately $10 \mu\text{s}$. It is to be noted, however, that these results were also obtained when the crystal was viewed by the detector through the cylindrical surface (in a direction in which Laser action could not be taking place), and hence it is concluded that there was no Laser action taking place, but only the fluorescence processes.

In a direct comparison of the results of the two experiments, the outstanding differences between the results occurs in the time interval between 0 and $5 \mu\text{s}$ of the pump pulse start. In the case of the paraboloid

system, there always existed a sharp pulse on the initiation of the trace quite similar in form and timing to the pump pulse. Also, no evidence could be found for the existence of both time constants observed in the other experimental method. A modification of the paraboloid experiment was conducted in which the Ruby crystal was replaced by a second crystal which was unsilvered and therefore of extremely poor characteristics so far as lasing is concerned. The results in this case were similar to that for the quality crystal. Hence, the conclusion was reached that the pulse did not indicate Laser action. As an explanation for the pulse, it is suggested that some light leakage took place in spite of efforts to prevent the same, such that both the Ruby output and the pump input were both available to the detector system. In order to explain the double time constant of the other experiment, it is suggested that because of the very close coupling, the decay from one of the higher excited states is being observed.

Since the results of these experiments proved to be negative, it is of interest to determine the extent to which the selected crystals can be pumped by the selected source. To determine this level, it is only necessary to determine the pump power available and the number of process atoms in the crystal. To do this rigorously, it would be necessary to write an expression for the pump pulse, Figure 12, a, in the form $n e^{-bt}$, where n and b are chosen to give the observed intensity, and to employ the analytic expression for a Planck radiator at 28,000°K; then, after multiplying and integrating over time and wavelength, determine the power available at each wavelength. In addition, the pumping efficiency per atom and the crystal quality would have to be introduced. Here, it is assumed that the spectral radiance of the pump, Figure 14, is constant in each of the wavelength intervals of interest, that is, the radiance of the source is constant at 3,000 watts/mm²/steradian/micron in the frequency range of 372 to 416 mμ, and is constant at 1200 watts/mm²/steradian/micron from 520 to 590 mμ. These wavelength intervals are determined from the energy diagram for Ruby shown in Figure 15. Finally, it is assumed that the pumping efficiency is 100% and that the above radiances are constant over a pulse duration time of .5 μs. It can be readily seen that the assumptions are quite optimistic.

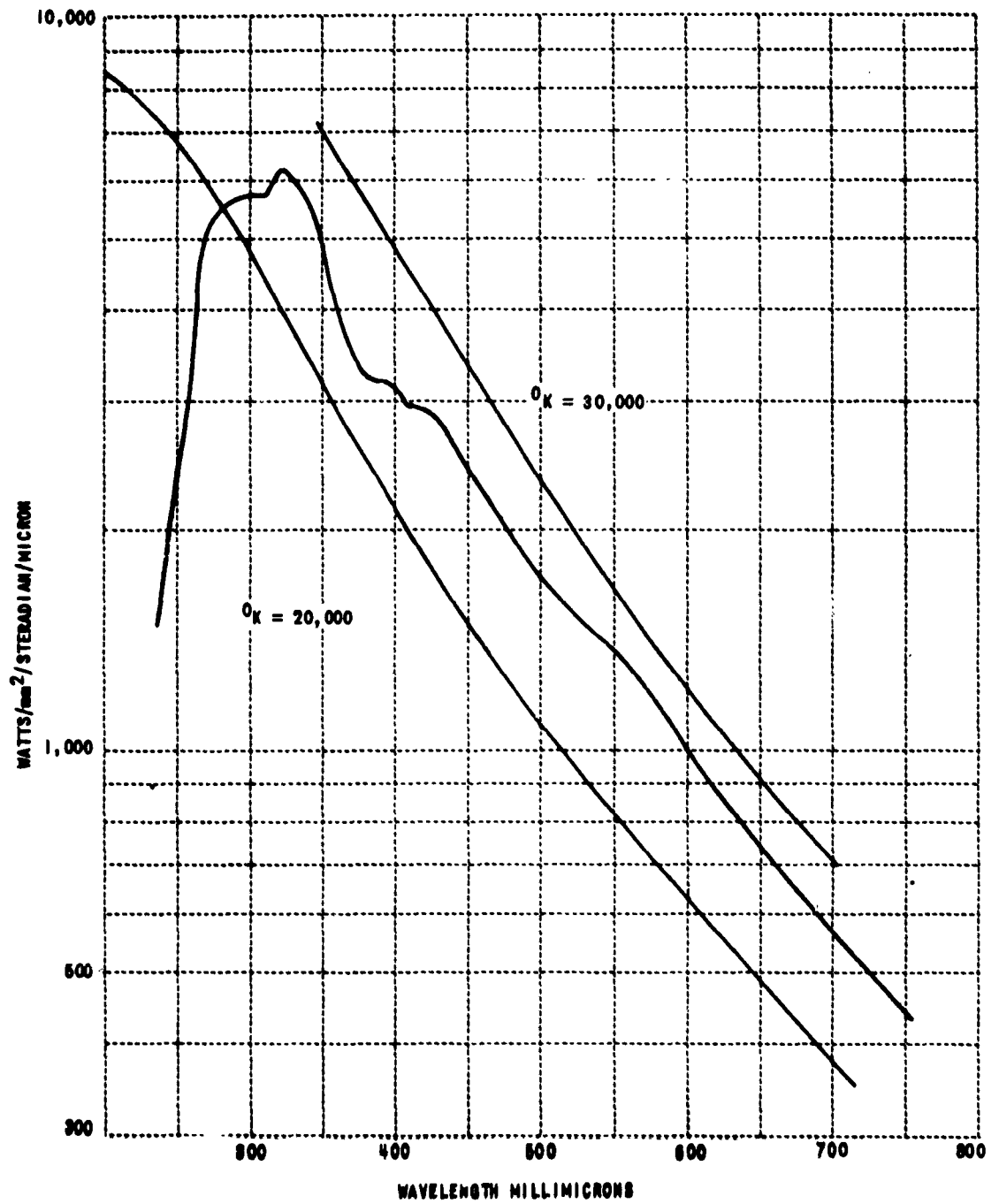


Figure 14 SPECTRAL RADIANCE OF THE ARC SOURCE

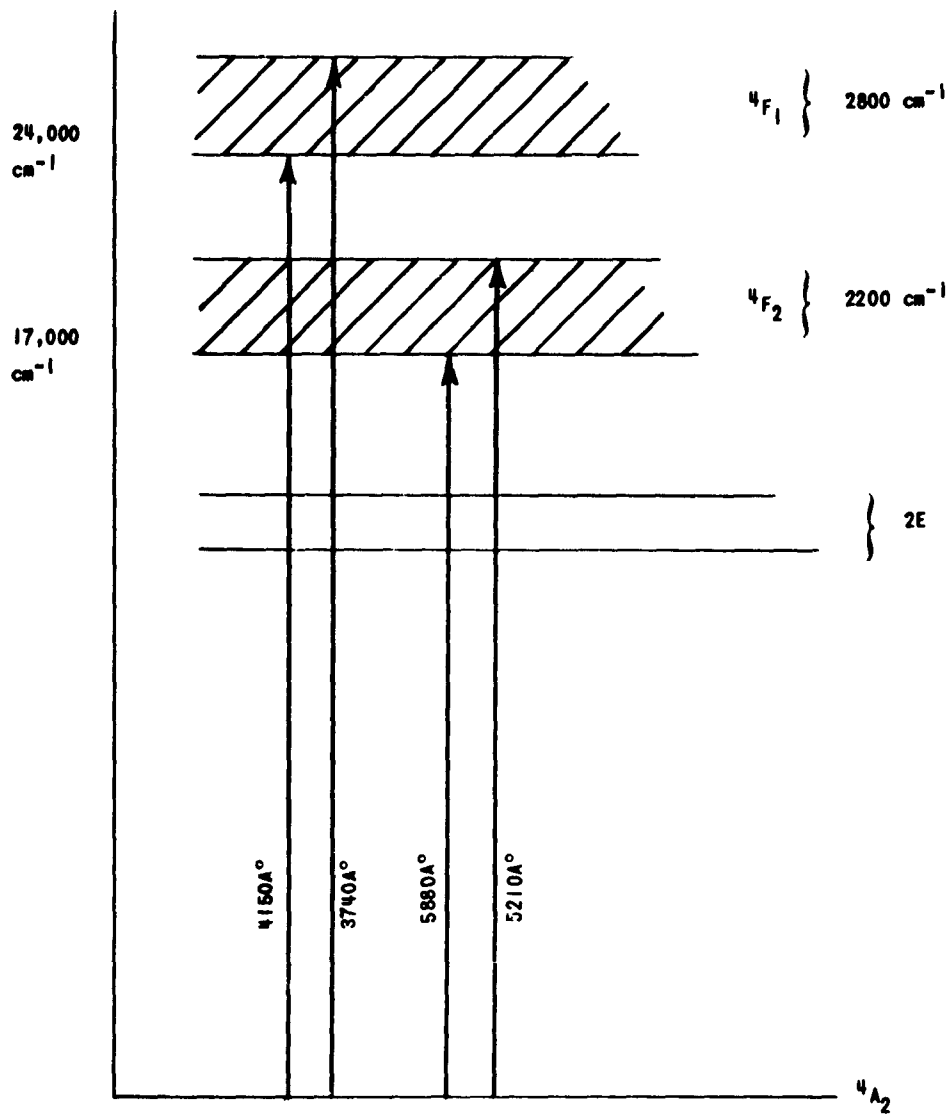


Figure 15 ENERGY LEVEL DIAGRAM FOR RUBY

Now the energy available in each of the pumping intervals can be determined by the data above, the source size, and the solid angle illuminated. Thus:

$$\text{Energy} = \text{Source Size} \times \text{Solid Angle} \times \text{Wavelength Interval} \times \text{Radiance} \times \text{Time.}$$

The source size for the spark lamp is approximately $.6 \pi \text{ mm}^2$, while the solid angle is approximately 2π steradians. Hence, for the Blue interval:

$$\begin{aligned} E &= .6 \pi \times 2 \pi \times \frac{40}{1000} \times 3000 \times 5 \times 10^{-7} \\ &= 7.2 \times 10^{-4} \text{ watt sec.} \end{aligned}$$

and, similarly, for the Green interval,

$$E = 5 \times 10^{-4} \text{ watt sec.}$$

Now the average photon energy in each frequency band is

$$\begin{aligned} E &= h\nu = \frac{hc}{\lambda} \\ E &= \frac{(6.6 \times 10^{-34} \text{ joules}^{-\text{sec.}} \times 3 \times 10^{16} \text{ m}\mu/\text{sec.})}{550 \text{ m}\mu} \\ &= 3.6 \times 10^{-20} \text{ joules - green} \\ E &= \frac{(6.6 \times 10^{-34} \times 3 \times 10^{16})}{395} = 5 \times 10^{-20} \text{ joules - blue.} \end{aligned}$$

Assuming then, 100% pumping efficiency, all photons generating an excited atom and each excited atom falling to the metastable level before any fluorescence, the number of excited atoms is:

$$\begin{aligned} N &= N_1 + N_2 = \frac{7.2 \times 10^{-4}}{5 \times 10^{-20}} + \frac{5 \times 10^{-4}}{3.6 \times 10^{-20}} \\ &= 1.4 \times 10^{16} + 1.4 \times 10^{16} \\ &= 2.8 \times 10^{16} \text{ excited atoms} \end{aligned}$$

Now the molecular weight of Al is 26 and of O is 16. Hence, the molecular weight of Al_2O_3 is 100. Avogadro's number is 6.02×10^{23} ; hence, the number of atoms per mole of Al_2O_3 is $5 \times 6.02 \times 10^{23}$.

Hence, the number of chromium equivalents is

$$\frac{2}{5} \times 5 \times 6.02 \times 10^{23} = 12.04 \times 10^{23}.$$

Using the density of 3.97 for Al_2O_3 , the number of equivalent chromium atoms per cubic centimeter can be calculated as

$$2 \times 6.02 \times 10^{23} \frac{\text{atoms}}{\text{mole}} \times \frac{3.97 \text{ g/cm}^3}{100 \text{ g/mole}} = 47.8 \times 10^{21} \text{ atoms/cm}^2.$$

Since the doping employed is .04%, the number of chromium atoms present in the Ruby is 2×10^{19} atoms/cc.

The crystal employed had a volume of $.4 \text{ cm}^3$. Hence, the number of excitable atoms was $.8 \approx 1 \times 10^{19}$ atoms, which is approximately 100 times the number that can be pumped by the arc source. Hence, an increase in radiance is required or, just as effectively, a volume reduction of 100X is required. However, with the reduction in volume by 100 times, assuming 100% Laser efficiency and a $.1 \mu\text{s}$ output pulse, the peak power output would be

$$\frac{4 \times 10^{16} \times 6.6 \times 10^{-34} \text{ joule} \times 3 \times 10^{16} \text{ m}\mu}{700 \text{ m}\mu \times 1 \times 10^{-7} \text{ sec.}}$$

$$= \frac{79.2}{70} \times \frac{10^{-3}}{10^{-7}} \approx 10^4 \text{ watts peak power}$$

Even under all the optimistic assumptions made, this level of power is at least three orders of magnitude less than can be obtained in present single-pulse systems employing the "Q spoiling" techniques noted earlier. However, the calculations do show that the assumptions leading to the undertaking of this program were optimistic and, with Ruby as the active material, lasing results should not have been expected.

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